10/536760

JC06 Rec'd PCT/PTO 26 MAY 2005

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Description

METHOD OF SYSTEMS ANALYSIS FOR DETERMINING MEASURED VARIABLES

The invention relates to a method and a device for designing a technical system, and a corresponding computer program product.

In the description of a technical system, for example a power station, reference is made to various parameters such as, for example, pressures, mass flows, etc. The parameters obey certain physical laws, such as for example those of mass or energy balances, which can be expressed by a system of equations. The solutions of this system of equations are the state variables of the technical system. From these state variables it is possible in turn to calculate diagnostic variables relevant for the operation of the technical system, such as for example the efficiency of a power station. The specific state of a technical system can, furthermore, be sensed by measurements. The measured variables of the measurements could directly reflect the value of a state variable; but it is also possible for measured variables which are derived from the state variables to be measured. For example, it is possible to measure the temperature of a technical system whereas the actual system state variables are the enthalpy and the pressure. In order to determine the state variables from the measured variables, one generally carries out a measurement and looks for the values of the state variables which solve the system of equations, and for which the derived measured variables lie closest to the measured values determined by the measurement (see for example VDI Guideline 2048).

The problem can arise, due to the number of equations in the

system of equations being too small, or too small a number of measurement points, that individual state variables or individual diagnostic variables remain indeterminate. In addition, the state variables or diagnostic variables, as applicable, may be subject to great uncertainty, because of measurement errors. It is therefore necessary to decide which measurements would permit the precision of certain state variables to be improved, or would permit any determination at all of certain state variables. For this purpose, it is usual to fall back on the advice of experienced engineers, and the suggestions of these engineers can be checked by simulation programs. However, this requires time-consuming analyses.

The object of the invention is therefore to specify a method for designing a technical system by which a systematic determination is made of how the measurements of individual measured variables influence the parameters of the technical system.

This object is achieved in accordance with the features of the independent claims. Developments of the invention are defined in the subclaims.

The method in accordance with the invention is for use in designing a technical system which is characterized by parameters, comprising state variables and diagnostic variables which are dependent on the state variables. Here, the term designing means, in particular, the analysis and/or changing of the technical system, in particular the analysis and changing of the measurements made in the technical system. In this situation, the technical system is specified by a system of equations, whereby the state variables are the solution of the system of equations. Incorporated into the design of the

technical system is a measurement 'park' which includes first measured variables, whereby these first measured variables are measured in the technical system with a prescribed precision. In addition, second measured variables, which are dependent on the state variables, can be measured in the technical system with a prescribed accuracy.

In the method in accordance with the invention, first sensitivity variables are determined for the first measured variables and/or second sensitivity variables are determined for the second measured variables whereby, for the purpose of defining the first sensitivity variables, a determination is made of the extent to which a change in the accuracy of the measurement of the first measured variables influences at least one selected parameter, and for the purpose of defining the second sensitivity variables, a determination is made of the extent to which the measurement of the second measured variables influences at least one selected parameter. The measurement park is then amended, depending on the first and/or the second sensitivity variables, in such a way that the accuracy of one or more of the first measured variables is changed, and/or one or more of the first measured variables is taken out of the measurement park and/or one or more of the second measured variables is added into the measurement park. This amended measurement park is used for designing the technical system.

In a preferred form of embodiment, the accuracy of a first measured variable is preferably increased, if the first sensitivity variable for this measured variable lies within a predefined value range, and/or a first measured variable is taken out of the measurement park if the first sensitivity variable for this measured variable lies within a predefined

value range and/or a second measured variable is added into the measurement park if the second sensitivity variable for this measured variable lies within a predefined value range. It is thus possible in a simple manner, by the choice of different value ranges, to modify the design procedure appropriately for various user-specific requirements.

In a preferred form of embodiment, the technical system is specified by a system of equations H(x) = (H1(x) ... , Hn(x) = 0, where x = (x1, ...xn) is a vector which includes as components the state variables xi. It is noted at this point that all the indices i, j, k or l used below represent cardinal numbers.

For the purpose of carrying out the method in accordance with the invention in a preferred form of embodiment the following matrices are, in particular, calculated:

- a matrix *N* which spans the null space of the Jacobian matrix *H*,
- a matrix *W*, such that $W^T \cdot W$ is the inverse of the covariance matrix of the first measured variables $y_i = b_i(x)$, where the covariance matrix has as its entries the covariances $\sigma_{ij}^2 = E((y_i - E(y_i))(y_j - E(y_j)))$, where E(y) is the expected value of y;
- a matrix M which is the pseudoinverse matrix of $A = W \cdot Db \cdot N$, where *Db* is the Jacobian matrix of the first measured variables $y_i = b_i(x)$.

The terms null space, Jacobian matrix and inverse or pseudoinverse matrix, as applicable, have definitions which are familiar from the theory of matrix computations (see for example Gene H. Golub, Charles F. van Load: "Matrix

Computations", 3rd Edition, Baltimore, London; The Johns Hopkins University Press; 1996).

In a further preferred form of embodiment of the invention, the first sensitivity variables calculated in the technical system are in each case the ratio of the change in accuracy of a selected parameter to the change in accuracy of a first measured variable, where the selected parameter is a selected state variable, which can be determined via the first measured variables. The method is distinguished in this case by the fact that:

- at least one of the selected parameters is a selected state variable, which can be determined via the first measured variables;
- one or more of the first sensitivity variables $\Phi_{y_j x_1}$ represents in each case the ratio of the change in accuracy $\Delta\sigma_{11}^2/x_1 = \Delta E((x_1 - E(x_1))^2)/x_1$ of the selected state variable x_1 to the change in accuracy $\Delta\sigma_{jj}^2/y_j = \Delta E((y_j - E(y_j))^2)/y_j$ of a first measured variable y_j;
- the first sensitivity variables are determined from the following formula:

$$\Phi_{y_j x_1} = \frac{\sigma^2_{jj}}{\sigma^2_{11}} \cdot r^2_{1j}$$

where r_{1j} is the element in the 1th line and the jth column of the matrix $N \cdot M \cdot W$.

In a further form of embodiment, each of the first sensitivity variables represents the ratio of the change in the accuracy of a selected diagnostic variable to the change in the accuracy of a first measured variable, where the selected diagnostic variable can be determined via the first measured variables. In

this case, the method is distinguished by the fact that:

- at least one of the selected parameters is a selected diagnostic variable, which can be determined via the first measured variables;
- a matrix Dd is determined, this being the Jacobian matrix of the diagnostic variables $d_i=d_i(x)$;
- one or more of the first sensitivity variables $\Phi_{y_j d_n}$ represents in each case the ratio of the change in accuracy $\Delta\sigma_{nn}^2/d_n = \Delta E((d_n - E(d_n))^2)/d_n$ of the selected diagnostic variable d_n to the change in accuracy $\Delta\sigma_{jj}^2/y_j = \Delta E((y_j - E(y_j))^2)/y_j$ of a first measured variable y_j;
- the first sensitivity variables are determined by the following formula:

$$\Phi_{y_j d_n} = \frac{\sigma^2_{jj}}{\sigma^2_{nn}} \cdot s^2_{nj}$$

where s_{nj} is the element in the n^{th} line and the j^{th} column of $Dd \cdot N \cdot M \cdot W$.

In a further preferred form of embodiment, one or more of the second sensitivity variables each represents the variance of a selected state variable when a second measured variable is being added in, where the selected state variable can be determined via the first measured variables. The method is distinguished in this case by the fact that:

- at least one of the selected parameters is a selected state variable which can be determined via the first measured variables;
- one or more of the second sensitivity variables represents, in each case, the variance $\sigma_{k\text{->}x_l}^2$ of the selected state variable x_l when a second measured variable, the value of

which is a state variable x_k with the variance σ_k, is being added to the measurement park;

- the second sensitivity variables are determined by the following formula:

$$\sigma^2_{k->x1} = m_1^T \cdot m_1 - \frac{(m_k^T \cdot m_1)^2}{\sigma_k^2 + m_k^T \cdot m_k},$$

where m_i is the i^{th} column of the matrix $M^T \cdot N$.

In a further form of embodiment of the invention, one or more of the second sensitivity variables represents in each case the variance of a selected diagnostic variable when a second measured variable is being added in, where the selected diagnostic variable can be determined via the first measured variables. Here, the method is distinguished by the fact that:

- at least one of the selected parameters is a selected diagnostic variable which can be determined via the first measured variables;
- a matrix Dd, which is the Jacobian matrix of the diagnostic variables $d_i=d_i(x)$, is determined;
- one or more of the second sensitivity variables represents, in each case, the variance $\sigma_{k->dn}^2$ of the selected diagnostic variable d_n when a second measured variable, the value of which is a state variable x_k and which has a variance σ_k is being added to the measurement park;
- the second sensitivity variables are determined by the following formula:

$$\sigma^2_{k->dn} = q_n^T \cdot q_n - \frac{(m_k^T \cdot q_n)^2}{\sigma^2_k + m_k^T \cdot m_k}$$

where m_i is the i^{th} column of the matrix $M^T \cdot N^T$, and q_n is the n^{th} column of the matrix and $M^T \cdot N^T \cdot Dd^T$.

The case can now arise in which the selected parameter of the technical system is a state variable which cannot be determined via the first measured variables. In this case, the first step is to determine a second measured variable, the value of which is a state variable, and which is to be added into the measurement park to enable the selected parameter to be uniquely determined. The method by which this case is taken into account is distinguished by the fact that:

- at least one of the selected parameters is a selected state variable which cannot be determined via the first measured variables;
- a matrix P, which is the orthogonal projection onto the null space of A, is determined;
- a second measured variable is determined, the value of which is a state variable x_k, and which is to be added into the measurement park so that the selected state variable can be uniquely determined;
- one of the second sensitivity variables represents the variance $\sigma_{k->x1}{}^2$ of the selected state variable when the second measured variable x_k which has been determined, and which has the variance σ_k, is being added to the measurement park;
- the second sensitivity variable is determined by the following formula:

$$\sigma^2_{k->x1} = \sigma^2_k \cdot \frac{\|p\|^2}{\|p_k\|^2} + \left\| m_1 - \frac{\|p\|}{\|p_k\|} m_k \right\|^2,$$

with $p = Pn_1$, where n_1 is the 1^{th} column of the matrix N^T, and

m_i is the i^{th} column of the matrix $M^T \cdot N^T$ and p_k is the k^{th} column of the matrix $P \cdot N^T$.

The further case can arise in which the selected parameter is a diagnostic variable which cannot be determined via the first measured variable. In this case, the first step is to determine a second measured variable, the value of which is a state variable, and which is to be added into the measurement park. The method by which this case is taken into account is distinguished by the fact that:

- at least one of the selected parameters is a selected diagnostic variable which cannot be determined via the first measured variables;
- a matrix Dd, which is the Jacobian matrix of the diagnostic variables $d_i = d_i(x)$, is determined;
- a matrix P, which is the orthogonal projection onto the null space of A, is determined;
- a second measured variable is determined, the value of which is a state variable x_k, and which is to be added into the measurement park so that the selected diagnostic variable can be uniquely determined;
- one of the second sensitivity variables represents the variance $\sigma_{k\text{->}dn}^2$ of the selected diagnostic variable d_n when the second measured variable x_k which has been determined, and which has the variance σ_k, is being added into the measurement park;
- the second sensitivity variable is determined by the following formula:

$$\sigma^2_{k\text{->}dn} = \sigma^2_k \cdot \frac{\|p\|^2}{\|p_k\|^2} + \left\| M^T \cdot c_n - \frac{\|p\|}{\|p_k\|} m_k \right\|^2,$$

with $p = Pc_n$, where c_n is the n^th column of the matrix $N^T \cdot Dd^T$, m_k is the k^th column of the matrix $M^T \cdot N^T$ and p_k is the k^th column of the matrix $P \cdot N^T$.

In the last two mentioned forms of embodiment, the determination of the second measured variable is preferably made by searching the matrix $P \cdot N^T$ for the column for which p is linearly dependent on the vector which the column represents, and the index of this column then gives the second measured variable which is to be added to the measurement park.

In a particularly preferred embodiment of the invention, in those forms of embodiment for which the variance of selected parameters is determined as the second sensitivity variable when second measured variables are being added in, 1% of the value of the second measured variable is taken as the standard deviation for the second measured variables which are to be added in.

It should be remarked at this point that the correctness of all the formulae used above can be demonstrated mathematically.

In addition to the method described above, the invention also relates to a device for carrying out the method in accordance with the invention. Furthermore, the invention covers a computer program product which has a storage medium on which is stored a computer program, which can be executed on a computer and by which the method in accordance with the invention can be performed.

Exemplary embodiments of the invention are explained and illustrated below by reference to the drawings

These show:

Fig. 1 the schematic structure of a technical system which is analyzed by means of the method in accordance with the invention.

Fig. 2 a processor unit for carrying out the method in accordance with the invention.

The technical system shown in Fig. 1 relates to a heating system in a power station, with two heating surfaces 1 and 2 connected one after the other, with a gas stream G and a water stream W flowing past these heating surfaces in opposite directions from each other.

The technical system is characterized by the following state variables:

$m_{W,in}$ mass flow of the water when it enters into the heating system;

$m_{W,out}$ mass flow of the water when it leaves the heating system;

$h_{W,in}$ specific enthalpy of the water when it enters into the heating system;

$h_{W,middle}$ specific enthalpy of the water between the two heating surfaces 1 and 2;

$h_{W,out}$ specific enthalpy of the water when it leaves the heating system;

m_G mass flow of the gas in the heating system;

$h_{G,in}$ specific enthalpy of the gas when it enters into the heating system;

$h_{G,middle}$ specific enthalpy of the gas between the two heating surfaces 1 and 2;

$h_{G,out}$ specific enthalpy of the gas when it leaves the heating system.

The state variables are the variables in a system of equations ***H(x)=0***, which includes the following physical balance equations:

Mass balance for the water in the heating system:

$$m_{W,in} - m_{W,out} = 0;$$

Enthalpy balance at the first heating surface:

$$m_G \cdot (h_{G,in} - h_{G,middle}) - m_{W,out} \cdot (h_{W,out} - h_{W,middle}) = 0;$$

Enthalpy balance at the second heating surface:

$$m_G \cdot (h_{G,middle} - h_{G,out}) - m_{W,in} \cdot (h_{W,middle} - h_{W,in}) = 0.$$

The following set operating points of the technical system are considered, where the values shown below for the state variables represent a solution to the above system of equations:

$m_{W,in}$	$m_{W,out}$	$h_{W,in}$	$h_{W,middle}$	$h_{W,out}$	m_G	$h_{G,in}$	$h_{G,middle}$	$h_{G,out}$
100	100	200	300	400	50	1000	800	600

Apart from the state variables identified above, the technical

system is further characterized by a diagnostic value which, in the present case, represents the relative heat transfer of the gas which is flowing through. This heat transfer W can be described by the following formula:

$$W = \frac{h_{G,in} - h_{G,out}}{h_{G,in}}$$

The following first measured variables are measured in the technical system with a standard deviation in each case of 1% relative to the setpoint value concerned:

Enthalpy flow for the water on entry into the heating system:
$m_{W,in} \cdot h_{W,in}$;

Mass flow of the water on entry into the heating system:
$m_{W,in}$

Enthalpy flow for the water on leaving the heating system:
$m_{W,out} \cdot h_{W,out}$;

mass flow of the gas:
m_G;

Enthalpy flow of the gas on entry into the heating system:
$m_G \cdot h_{G,in}$

Using the formula quoted above for the relative heat transfer W with the setpoint values gives $W = 0.4$.

Because the standard deviations used are 1%, the measurement of the relative heat transfer leads to a measured value of 0.4 with a standard deviation of 0.0098.

In a first variant of the method in accordance with the invention, the sensitivity variable used for a first measured quantity is in each case the ratio of the change in accuracy of the diagnostic value *W* to the change in accuracy of the first measured value.

This gives the following values:

Sensitivity variable for the enthalpy flow of the water on entry into the heating system: 0.167.

Sensitivity variable for the mass flow of the water on entry into the heating system: 0.0.

Sensitivity variable for the enthalpy flow of the water on leaving the heating system: 0.667.

Sensitivity variable for the mass flow of the gas: 0.0

Sensitivity variable for the enthalpy flow of the gas on entry into the heating system: 0.167.

It will be seen that the sensitivity variable for the enthalpy flow of the water on leaving the heating system has the greatest value. This means that a change in the accuracy of the measurement of the enthalpy flow of the water on leaving the heating system has the greatest influence on the accuracy of the measurement of the relative heat transfer. It follows that an improvement in the measurement accuracy of the enthalpy flow of the water on leaving the heating system will be most effective in producing an improvement in the accuracy of the diagnostic value. By contrast, the measurements of the mass

flows have a sensitivity value of 0, and thus have no affects on the accuracy of the diagnostic value W.

In a further form of embodiment of the method in accordance with the invention, the variances of the relative heat transfer are calculated as the sensitivity variables, on the assumption that in the technical system a state variable is being added in to the first measured variables as a second measured variable with a standard deviation of 1% relative to the setpoint value. Below are given the standard deviations (square roots of the variances) when individual state variables are being added in:

Add in $m_{W,in}$: 0.0098;

Add in $m_{W,out}$: 0.0098;

Add in $h_{W,in}$: 0.0095;

Add in $h_{W,out}$: 0.0086;

Add in m_G: 0.0098;

Add in $h_{G,in}$: 0.0095;

Add in $h_{G,out}$: 0.0062;

The addition of $h_{W,middle}$ and $h_{G,middle}$ is not considered because these state variables are not uniquely determined by the measured variables. It can be seen that the introduction of the measurement of $h_{G,out}$ gives the smallest standard deviation for the relative heat transfer. As a consequence, the measurement of $h_{G,out}$ is added into the measurement park for the first measurements.

In a further form of embodiment of the invention, consideration is now given to state variables which are not uniquely determined by the first measured variables of the technical system. In this case, these are the state variables $h_{W,middle}$ and $h_{G,middle}$. A first step is now used to determine the measured variables which must be added in for the state variables $h_{W,middle}$ and $h_{G,middle}$ to be uniquely determined. For this purpose, a calculation is performed in accordance with claim 11.

It turns out that a measurement of $h_{W,middle}$ or $h_{G,middle}$ is in each case sufficient to determine the two state variables $h_{W,middle}$ and $h_{G,middle}$. Making the assumption of a standard deviation of 1% for the measurement of $h_{W,middle}$ or $h_{G,middle}$, as applicable, gives:

- in the case of a measurement of $h_{W,middle}$, a standard deviation for $h_{W,middle}$ of 3.0, and a standard deviation for $h_{G,middle}$ of 17.34;

- in the case of a measurement of $h_{G,middle}$, a standard deviation for $h_{W,middle}$ of 9.06, and a standard deviation for $h_{G,middle}$ of 8.0.

From this it can be seen that for an exact determination of $h_{W,middle}$ it is preferable to actually measure $h_{W,middle}$, whereas for an exact determination of $h_{G,middle}$ it is preferable to add also $h_{G,middle}$ as a measurement in the measurement park.

The method described above permits a systematic and rapid search for measurement points by which the accuracy of selected state variables or diagnostic variables, as applicable, can be improved. It is thus no longer necessary to fall back on the

experience of engineers in order to decide which measured variables should be added into a measurement park, or which measurement accuracies should preferably be improved, as applicable.

Fig. 2 shows a processor unit PRZE for performing the method in accordance with the invention. The processor unit PRZE incorporates a processor CPU, a memory MEM, and an input / output interface IOS, which is used in various ways via an interface IFC: an output is shown visually on a monitor MON via a graphic interface, and/or is output on a printer. Inputs are made via a mouse MAS or a keyboard TAST. The processor unit PRZE also provides a data bus BUS, which establishes the link between a memory MEM, the processor CPU and the input/output interface IOS. Further, additional components can be connected to the data bus, for example additional memory, data storage (hard disk) or scanners.